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A CALORIMETRIC INVESTIGATION OF SOME PROBLEMS ASSOCIATED WITH A LOW-DENSITY HYPERVELOCITY WIND TUNNEL

By

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von Kármán Gas Dynamics Facility
ARO, Inc.

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ARNOLD ENGINEERING DEVELOPMENT CENTER

AIR FORCE SYSTEMS COMMAND

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FOREWORD

The authors are grateful to those members of the Research Branch who, from time to time, assisted with the experimental work. Particular thanks are due Max Kinslow, who initially suggested the investigation and who contributed materially to the design of the apparatus, and to Loren Davis and Bill Carden, who assisted in obtaining data and analysing the results.

ABSTRACT

Both total calorimeter and calorimeter probe experiments have been carried out to more adequately establish the flow properties in an arc-heated, low-density, hypervelocity wind tunnel. Total calorimeter results show that for a sufficiently long stilling chamber, total enthalpy at the throat can be accurately determined from the total pressure, mass flow rate, and sonic throat area by use of the continuity equation. Unfortunately, the physical size of the calorimeter probe as compared to the size of the test section altered the test-section flow properties so that no useful calibration data were obtained by this means. It is concluded, however, that such a probe could yield useful calibration data in a sufficiently large wind tunnel.

PUBLICATION REVIEW

This report has been reviewed and publication is approved.

D.R. Eastman, Jr. — Jean A. Jack

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CONTENTS

		Page
	ABSTRACT	v
	NOMENCLATURE	ix
1.0	INTRODUCTION	1
2.0	TOTAL CALORIMETRY	
	2.1 Apparatus	3
	2.2 Instrumentation	3
	2.3 Procedure	4
	2.4 Results and Discussion	5
3.0	PROBE CALORIMETRY	
	3.1 Apparatus	7
	3.2 Instrumentation	8
	3.3 Procedure	8
	3.4 Results and Discussion	8
4.0	CONCLUSIONS	10
	REFERENCES	11
	APPENDIX I: A Method for the Calculation of Stagnation Enthalpy	13
	APPENDIX II: Sonic Point Location	17

ILLUSTRATIONS

Figure		
1.	Total Calorimeter	19
2.	Total Calorimeter Results for 2-in. Stilling Chamber	20
3.	Total Calorimeter Results for 3-in. Stilling Chamber	21
4.	Total Calorimeter Results for 5-in. Stilling Chamber	22
5.	Total Calorimeter Results for 8-in. Stilling Chamber	23
6.	Energy Balance Results	24
7.	Combined Heating Efficiency of Arc Heater and Stilling Chamber	25
8.	Calorimeter Probe	26
9.	Calorimeter Probe Results	27

NOMENCLATURE

A	Area
a	Speed of sound
C_D	Discharge coefficient
D	Diameter
f	Friction coefficient
H	Enthalpy
L	Length of stilling chamber
M	Mach number
$\dot{m}$	Mass flow rate
p	Pressure
S	Entropy
T	Temperature
U	Velocity
x	Axial position along nozzle
γ	Ratio of specific heats
ρ	Density

SUBSCRIPT

o	Isentropic stagnation conditions

SUPERSCRIPT

*	Sonic conditions

1.0 INTRODUCTION

A small, continuous-flow, low-density, hypervelocity wind tunnel is in operation at the von Kármán Gas Dynamics Facility (VKF), Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC). A description of this tunnel, commonly referred to as the LDH tunnel, and the results of a preliminary calibration program have been presented in Ref. 1. Briefly, the tunnel consists of: (1) a direct-current, electric arc heater, (2) a stilling chamber, (3) a conical expansion nozzle of 15-deg half angle*, (4) a test section with model and probe traversing mechanism, (5) a vacuum pumping system, and (6) necessary instrumentation. The present normal range of flow conditions using nitrogen as the working fluid is as follows:

total temperature	2000 - 4000 °K
Mach number	8.8 to 10.5
stagnation enthalpy	1000 to 2100 Btu/lb
velocity	7,000 to 10,000 ft/sec
static pressure	10 to 65 microns Hg
static density	(2 to 13.8) x 10^{-6} lb/ft^3
unit Reynolds number	260 to 1140 per in.
diameter of uniform core	0.5 to 1.2 in. at test section

Several problems which are common to all hypervelocity wind tunnels make it difficult to establish flow properties with absolute certainty. Paramount among these has been the inability to make sure definition of the effective reservoir conditions. In the past, based on reasonably secure grounds (Ref. 1), the measured value of stilling chamber pressure has been used as the effective total pressure, and the fluid in the reservoir has been assumed to be in thermo-chemical equilibrium. Because of its high level, no direct measure of the reservoir temperature has been possible. Thus, it has been necessary to resort to an indirect means of determining the total enthalpy from directly measured quantities; i.e., the measured value of stilling chamber pressure, mass flow rate, and nozzle throat diameter are used, and from the tabulated properties of the gas (Ref. 2) a value of total enthalpy is found which will satisfy the continuity equation with sonic flow at the throat. A convenient method which has been developed for doing this is given in Ref. 3, and a refinement is given in Appendix I. It has

*A contoured nozzle has been recently installed.

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been recognized that several possible sources of error are inherent in this procedure as follows:

1. Despite the fact that a rather large stilling chamber was originally provided (5-in. length or approximately 25 times the exit diameter of a typical nozzle-anode of the arc heater), nonequilibrium and nonuniformity of the working gas may persist from the arc heater to the vicinity of the sonic throat.

2. The effective sonic flow area may not coincide with the geometric nozzle throat. This may occur because of non-negligible boundary-layer displacement thickness, diabatic flow, and change in physical size of the nozzle throat during a run.

3. The distribution of flow properties may not be uniform across the sonic throat.

4. Nonisentropic flow in the converging section may cause the effective reservoir pressure to differ from the measured stilling chamber pressure.

Other uncertainties arise in the determination of the test-section flow properties which are finally calculated by the usual method from reservoir conditions and measured impact pressures. Several possible sources of error generally inherent in this procedure are as follows:

1. Corrections for viscous and thermal effects on impact pressure probes may introduce small errors (Refs. 3 and 4).

2. Uncertainties may exist regarding the degree to which the flow is frozen (Ref. 1).

3. The assumption of adiabatic expansion may not be entirely valid.

As part of the LDH tunnel calibration program, two series of calorimetric experiments have been designed and carried out with the following objectives in mind:

1. Total Calorimeter Series: to establish the stilling chamber length required to justify the assumption of uniformity and equilibrium in the reservoir and to provide an experimental check on the commonly used method for determination of total enthalpy therein

2. Calorimeter Probe Series: to obtain an independent measurement in the expanded flow which would tend to reflect the effects of nonisentropic and frozen expansion

The results and conclusions derived from these experiments should be of general interest to persons associated with low-density and high-enthalpy wind tunnels.

2.0 TOTAL CALORIMETRY

2.1 APPARATUS

To simulate conditions in the reservoir of the LDH tunnel and, at the same time, to provide a means of independently arriving at the total enthalpy of the exiting gas, the apparatus shown in Fig. 1 was designed and built. This apparatus, for all practical purposes, duplicates the LDH tunnel upstream of the geometric throat of the nozzle except that provisions were made for interchangeable stilling chambers of different lengths. Downstream of this point the similarity ends, in that the diverging section of the nozzle is replaced by a thermally insulated heat exchanger.

Calculations have indicated that as a result of heat transfer, etc. (see Appendix II) the sonic station is displaced a negligible amount upstream of the geometric throat. Thus, it is reasonable to assume that all flow properties upstream of the throat (including total enthalpy) are identical to those in the LDH tunnel for a given stilling chamber pressure, mass flow rate, stilling chamber length, and throat size.

This apparatus facilitates the determination of the total enthalpy in the following manner. The energy, per unit time, transported away from the downstream heat exchanger, or calorimeter, can be calculated from the measured cooling water flow rate and temperature rise. Also, since the exciting gas is relatively cool, the total temperature can be measured, which, together with the known mass flow rate, determines the energy per unit time transported away by the gas. In steady-state operation after all parts of the apparatus have reached an equilibrium temperature, the sum of these can be assumed to be equal to the energy per unit time transported into the calorimeter by the working gas. Thus, by dividing this sum by the mass flow rate, an average value for the total enthalpy at the throat can be determined.

2.2 INSTRUMENTATION

To obtain some insurance that all the energy in the gas was accounted for in the downstream calorimeter, the system was instrumented so that an energy balance on the entire system could be achieved; i.e., provisions were made to measure the torch voltage and current and the cooling water temperature rise and flow rate in the torch, stilling chamber, and throat section in addition to those measurements in the calorimeter (see Fig. 1 for location of thermocouples). A complete listing of the instrumentation is as follows:

1. water and gas temperature: copper-constantan thermocouples with L and N servopotentiometer readout
2. gas flow rate: calibrated orifice and CEC electromanometer
3. water flow rates: calibrated volume and stop watch
4. stilling chamber and calorimeter pressures: CEC electromanometer
5. arc-heater current: 1000 amp, 50-mv shunt, and L and N strip chart
6. arc-heater voltage: resistance bridge and L and N strip chart

2.3 PROCEDURE

Because the calculation of total enthalpy from the mass flow rate and stilling chamber pressure is extremely sensitive to throat area, some effort was devoted to its measurement under simulated operating conditions; i.e., a taper gage was used to measure its diameter under varying temperature conditions. Although there was some scatter in the results, it was concluded that the effect of temperature on throat size was small and that a throat diameter of 0.103 in. could be used as a typical value without introducing more than ±1 percent error in the calculated enthalpy.

The apparatus was then placed in operation, and a typical set of data was taken in the following manner. The mass flow rate was set, and the power input to the torch was adjusted to give a desired stilling chamber pressure. Then the calorimeter pressure was adjusted so that it was just low enough to ensure sonic flow at the nozzle throat. To minimize errors resulting from heat transfer between the throat section and the calorimeter, the cooling water flow rates were adjusted so that their respective, adjacent flanges were almost of equal temperatures (see Fig. 1, thermocouples 4 and 5). Finally, after the apparatus had reached an equilibrium temperature, all the necessary measurements were made and recorded. Data were taken in this manner over a range of mass flow rates and stilling chamber pressures for each of the four stilling chamber lengths.

2.4 RESULTS AND DISCUSSION

The results of these experiments are shown in Figs. 2 through 5 inclusively, where the total enthalpy is plotted as a function of the ratio $\dot{m}/p_o$ for the 2-in., 3-in., 5-in., and 8-in. stilling chamber lengths, respectively. Also shown by the solid-line curve is the theoretical value of enthalpy that should exist for a given $\dot{m}/p_o$ (see Appendix I) if uniform, equilibrium, sonic flow exists at the nozzle minimum area. It is to be noted that the experimentally determined total enthalpy is greater than the theoretical value for the 2-in. length but appears to approach the theoretical value as a limit when the length is increased. For the 5-in. and 8-in. lengths, the agreement of measurement and theory is very good.

Consideration of the flow pattern in the stilling chamber reveals that such a trend might well be expected. Visualize a highly energetic, nonequilibrium, nonuniform, gas exiting the arc heater in a concentrated, pencil-like jet. Unless sufficient mixing length is provided for this high-speed flow to diffuse and nearly come to rest prior to entering the aerodynamic nozzle, it may be expected that such flow will pass the throat in this form. At a given set of conditions, this would result in the measurement of a falsely low value of p_o and lead to a high value of $\dot{m}/p_o$ (see Fig. 2). Moreover, unless the stilling chamber is sufficiently long, nonequilibrium of the working gas may persist to the vicinity of the aerodynamic throat. Only a small fraction of the gas need be dissociated or ionized to represent a significant amount of energy. This small fraction would be expected to result in little deviation of p_o from the equilibrium value so that the total enthalpy implied from the ratio $\dot{m}/p_o$ would be significantly less than that existing in reality.

Generally speaking, several factors could be expected to influence the length of stilling chamber required for uniformity and equilibrium to obtain prior to entrance of the working gas into the aerodynamic throat. Aside from the operating condition itself, the diameter of the arc-heater nozzle, the diameter of the aerodynamic throat, the amount of swirl (if any) given the gas in the arc heater, and the diameter of the stilling chamber might be governing factors. However, for the geometry and range of operating condition considered in the present case where there is no swirl and the plasma jet diameter is approximately 0. 26 in., it is apparent that a stilling chamber length of 5 in. $< L <$ 8 in. is sufficient to reach a satisfactory degree of uniformity and equilibrium since the trend in the data seems to approach a limiting value within this range. The earliest stilling chamber on the LDH tunnel was 5 in. in length, whereas the present chamber is 7 in. long.

The further fact that, in these limiting cases, the present experimental data agree almost perfectly with theory (see Fig. 5) has additional implications. It is immediately apparent that, for a sufficiently long stilling chamber and for the range of conditions considered, the ratio $\dot{m}/p_o$ can be used to predict an average value for total enthalpy at the throat with surprising accuracy. It is also apparent that the several factors expected to introduce errors in the theoretical value are either negligible or are compensating for each other. Since it is difficult to believe that such perfect compensation would result over the entire range of conditions for which data were obtained, it is implied that the flow at and immediately upstream of the throat does not deviate far from the idealized flow model; i.e., for all practical purposes, the flow is uniform and isentropic with a negligible boundary layer, the gas is in equilibrium, etc.

Unfortunately, the results of an overall energy balance, as shown in Fig. 6, for several typical operating conditions fail to entirely validate the preceding data. Before attempting to analyze these results, it might be well to mention the fact that the time required for all the necessary measurements resulted in less attention being given to maintaining steady water flow rates, etc. than was given when only calorimeter measurements were being made. Moreover, fluctuations in the voltage and current made it difficult to accurately determine the power input. With this in mind, it should be considered that the energy balance is not as accurate as the total enthalpy. A best straight line through the data points of Fig. 6 tends to show that approximately three percent of the energy input was left unaccounted for. However, data corresponding to the longer chambers do not show this discrepancy.

To ensure that this small amount of energy was not escaping in the gas exiting the calorimeter in a form the total-temperature probe would not reveal, an extension of the calorimeter was made. This extension consisted of a water-cooled tube with provisions to measure water temperature rise and flow rate and gas total temperature at the downstream end, similar to the original apparatus. Although the tube length was calculated to be of sufficient length to allow relaxation of any significant nonequilibrium vibrational energies, dissociation energies, etc., the results were negative. Thus, it could be assumed that, at worst, the three percent error could be distributed over the entire apparatus, which would imply that the experimental values of total enthalpy are approximately three percent low. This could be accounted for by a lag in the relaxation of vibrational energies at the throat entrance (Refs. 5 and 6).

It is also of interest to consider the overall heating efficiency of the arc heater and stilling chamber. This was obtained from the present data by dividing the energy per unit time transported past the throat by the power input. The efficiency versus the product of power input and stilling chamber length is shown for several typical conditions in Fig. 7. This does not represent a serious effort to correlate these results because no particular care was taken to assure consistency in the data relating to efficiency. The scatter in the results is easily explained. First, this method of plotting does not account for the many other variables expected to contribute to the heat losses. Secondly, the efficiency of the arc heater is highly dependent upon the precise shape and size of the electrodes. In many cases these were chosen to obtain stable operation at a given condition and were improper to give maximum efficiency of the arc heater itself. In other cases, the electrodes were of such a nature as to give near maximum efficiency. Despite the lack of correlation, the results serve to point out the low heating efficiency which can be expected when a relatively large stilling chamber is added to an arc heater. In the present case the efficiency varied from approximately 8 to 21 percent. It must be remembered that this result applies to the particular configuration tested, but qualitatively similar results could be expected in other cases.

3.0 PROBE CALORIMETRY

3.1 APPARATUS

As an outgrowth of the successful use of a mass-flow probe in obtaining useful calibration data in the LDH tunnel (i.e., apparent swallowing of the shock, no flow interference, see Ref. 1), the calorimeter probe shown in Fig. 8 was designed and built. The purpose of this probe was to determine the total energy in a known area of the expanded flow. It was thought that such information might serve to resolve uncertainties regarding nonisentropic and frozen flow in the assumed flow model.

The probe is axisymmetric and consists essentially of a water-cooled inner jacket and a water-cooled outer jacket with thermal insulation sandwiched in between. Each jacket is knife-edged at the front with a clearance of 0.002 to 0.005 in. to reduce heat transfer between jackets. Now, if the bow shock is swallowed, it can be assumed that the total energy per unit time entering the inner jacket is the product of the total enthalpy, probe entrance area, local free-stream density and velocity ($HA\rho U$). This product can be obtained from calculations based on an isentropic flow model, either in equilibrium or with the vibrational model frozen at the throat.

Similar to the total calorimeter, the assumption is made that the total energy entering the probe can be accounted for by measuring the water flow rate and temperature rise and the total temperature of the exiting gas. One fallacy here is that the mass flow rate of gas through the probe is a calculated value. However, since the principal part of the total energy is expected to be accounted for by the cooling water, this should introduce little error in the experimental data.

There are several points at which failure may occur when accurate data is desired with this probe. First, there is the fact that the bow shock may not be completely swallowed, although results from the mass flow probe mentioned previously indicated that it should be. Also, there is the possibility of heat transfer between the inner and outer shell which can, of course, be minimized by controlling the water flow rates so that a minimum temperature difference is maintained between them. Thirdly, it may be possible for energy to be frozen in certain modes that will not be detected by the total temperature probe at the exit. Finally, the probe must be relatively large, and there is the chance of distorting the nozzle flow approaching the probe. The last may occur because of blockage or the upstream influence of the flow field of the probe.

3.2 INSTRUMENTATION

Water and gas temperatures were measured by use of copper-constantan thermocouples read out on an L and N servopotentiometer. Water flow rates were measured with a stop watch and a calibrated volume.

3.3 PROCEDURE

With the probe located at a known position in the LDH tunnel test section and in the core of usable flow, a typical data point was taken in the following manner. A set of standard tunnel operating conditions was established, and the cooling water to the probe was adjusted so that the inlet and outlet water temperatures at the outer jacket were approximately equal to the corresponding ones at the inner jacket. After the probe had reached an equilibrium temperature throughout, the necessary measurements were made and recorded.

3.4 RESULTS AND DISCUSSION

A typical set of results taken in the manner described above is shown in Fig. 9 (the starred data points) where the quantity $HA\rho U$ is plotted versus the axial position of the probe entrance. In contrast, the solid-line curve shows the values of this quantity as calculated from previous impact-probe data. It is to be noted that the experimental results are consistently higher than the calculated values.

To determine if the discrepancy might be a result of heat transfer from the outer to the inner jacket of the probe, the cooling water flow rate to the outer jacket was increased so that its exit temperature was approximately 15°F cooler than that of the inner jacket. Under this condition one might expect that the net flow of heat would be from the inner to the outer jacket and that a resulting low experimental value for $HA\rho U$ would be found. There is no guarantee that this is the case; however, for nonuniform temperatures may have existed along the probe walls (see Fig. 8). The resulting data are shown by the squares in Fig. 9. Note that these results are somewhat lower than the previous ones but still higher than the calculated values. This demonstrates the possibility of heat transfer between the inner and outer jackets and a resulting need for refinements in the probe and/or instrumentation.

To find some additional explanation as to why the experimental results were high, the wall static pressure was measured at several points along the wind tunnel nozzle with the probe in place. It was found that the probe was of such a size as to cause a significant increase in these pressures in the upstream section of the nozzle ahead of the probe. Also, impact pressures were taken in front of the probe and were found to increase downstream toward the calorimeter probe.

One may assume that the impact pressures read from the small probe extending from the forward inlet of the calorimeter probe are indicative of a recompression of the nozzle flow caused by the shock wave of the calorimeter interacting with the nozzle boundary layer. Then one may consider this recompression either near isentropic or through a wave system of finite entropy gain. Proceeding from these assumptions, the local mass flow rates were recalculated, and the corresponding values of the quantity $HA\rho U$ are shown by the dotted curve of Fig. 9. While this curve is in better agreement with the experimental results, it leaves something to be desired.

Because of the uncertainties of the probe results arising from possible internal heat exchange, distorted nozzle flow field, and possible difference between effective entrance area and probe geometric entrance area, and also because the recalculated mass flow rates can, at best, be considered crude, this series of experiments was not pursued further. However, the data do look sufficiently good to suggest the feasibility of obtaining useful data by a refined calorimeter probe in a tunnel sufficiently large as compared to the probe itself.

4.0 CONCLUSIONS

It has been shown that a relatively long stilling chamber is required between an arc heater of the constricted-arc type and the aerodynamic throat of a hypervelocity wind tunnel to establish uniformity and equilibrium of the gas immediately upstream of the throat. Unfortunately, the addition of such stilling chambers leads to a relatively low overall heating efficiency (8 to 21 percent in the present series of tests). It has also been shown that, for a sufficiently long stilling chamber and for $p_o \approx 1$ atm and $h_o < 2000$ Btu/lb, the average total enthalpy can be predicted with surprising accuracy from the measured quantities p_o, $\dot{m}$, and the throat area. Arguments have been presented which favor the assumption of uniform flow properties (including total enthalpy) across the sonic throat when sufficiently long stilling chambers were used. Although some evidence was found that the experimentally determined total enthalpy might be as much as three percent low, it is suggested that this may represent freezing of the vibrational mode prior to reaching the throat. It was evident only in the cases of the shorter stilling chambers.

Several hypervelocity wind tunnels which have been reported in the literature have relatively short or no stilling chambers. The present results cast considerable doubt on the validity of flow properties based on assumed uniformity and equilibrium at the sonic throat in such instances. In the case of the LDH wind tunnel, it is apparent that the initial choice of 5 in. for the stilling chamber length was fortunate. Perhaps a slight increase in length would be more conservative for the present extended range of operating conditions. Unfortunately, such increased lengths lead to a penalty in attainable total enthalpy due to heat losses. Nonetheless, as a result of these experiments, the stilling chamber length was increased to 7 in. some time ago.

A calorimeter probe failed to provide useful calibration data in the present LDH tunnel. Besides problems arising from heat transfer within the probe itself, static- and impact-pressure measurements indicated that the probe was affecting flow conditions upstream of itself apparently because of its large size as compared to the diameter of the test-section flow. While no satisfactory calculation of the flow properties could be made under these conditions, the data agreed with crude calculations sufficiently well to imply the feasibility of using such a probe to assist in calibration of larger hypervelocity wind tunnels. The heat-transfer problems inherent in this type of probe seem to make it impractical to build one small enough for use in the present tunnel.

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APPENDIX I

A METHOD FOR THE CALCULATION OF STAGNATION ENTHALPY

If it is assumed that the flow in the stilling chamber is isentropic and adiabatic and furthermore, that the flow is in equilibrium, the following relationships may be made:

$$\begin{aligned} S_o &= S^* \\ p_o &= p_o^* \\ H_o &= H^* + 1/2\ a^{*2} \end{aligned} \qquad \text{(I-1)}$$

These relationships, together with the tabulated values of the thermodynamic properties of the working gas, may be used to calculate an effective total enthalpy for a given total pressure, mass flow rate, and sonic throat area.

A relationship between entropy, enthalpy, and pressure for nitrogen was obtained by fitting the tabulated thermodynamic properties of Ref. 2 to a smooth curve. The relationship obtained was:

$$F(H) = S - 7360.6\ (3.50 \log_{10} H - \log_{10} p) \qquad \text{(I-2)}$$

with

S in $ft^2/sec^2\ {}^\circ K$

H in ft^2/sec^2

p in atmospheres

A curve of F(H) vs H is independent of pressure up to the point where dissociation becomes appreciable and may be plotted on Cartesian coordinates to a large scale.

A calculation starting at the sonic point with tabulated values of T, a, ρ, H, and S gives the sonic throat (*) value of p_o from Eq. (I-2) and the relationships in Eq. (I-1).

In the nondissociated region the calculation is straightforward using the following procedure:

1) $H_o = H^* + 1/2\ a^{*2}$

2) $S_o = S^*$

3) $F(H_o)$ from the curve of $F(H)$ vs H

4) $p_o = \text{anti log} \left\{ \dfrac{F(H_o) - S_o + (7360.6)(3.5) \log H_o}{7360.6} \right\}$

In the dissociated region, an iterative procedure is required which consists of assuming a p_o for each sonic condition to obtain the value for $F(H_o)$. Values of p_o are then calculated using the procedure outlined above until convergence of assumed p_o and calculated p_o is reached.

When values of p_o and H_o are obtained for a range of ρ^* and a^*, a plot of $\frac{\rho^* a^*}{p_o}$ vs H_o may be made. It may be noted that

$$\frac{\rho^* a^*}{p_o} = \frac{\rho^* a^* A^*}{A^* p_o} = \frac{\dot{m}}{A^* p_o} \tag{I-3}$$

Equation (I-3) contains the measurable parameters, mass flow, throat area, and reservoir pressure. Figure I-1 is a curve of this parameter for the reservoir conditions encountered in the LDH tunnel where typically p_o = 0(1 atm). The curve is a unique relation in the nondissociating region. The LDH tunnel normally is within this region with only small dissociation effects at the higher enthalpy levels.

With the assumption that

$$C_D = 1$$

and

$$A^* = \text{constant} = \text{measured area}$$

a curve of $\dot{m}/p_o$ vs H_o may be drawn for a particular nozzle.

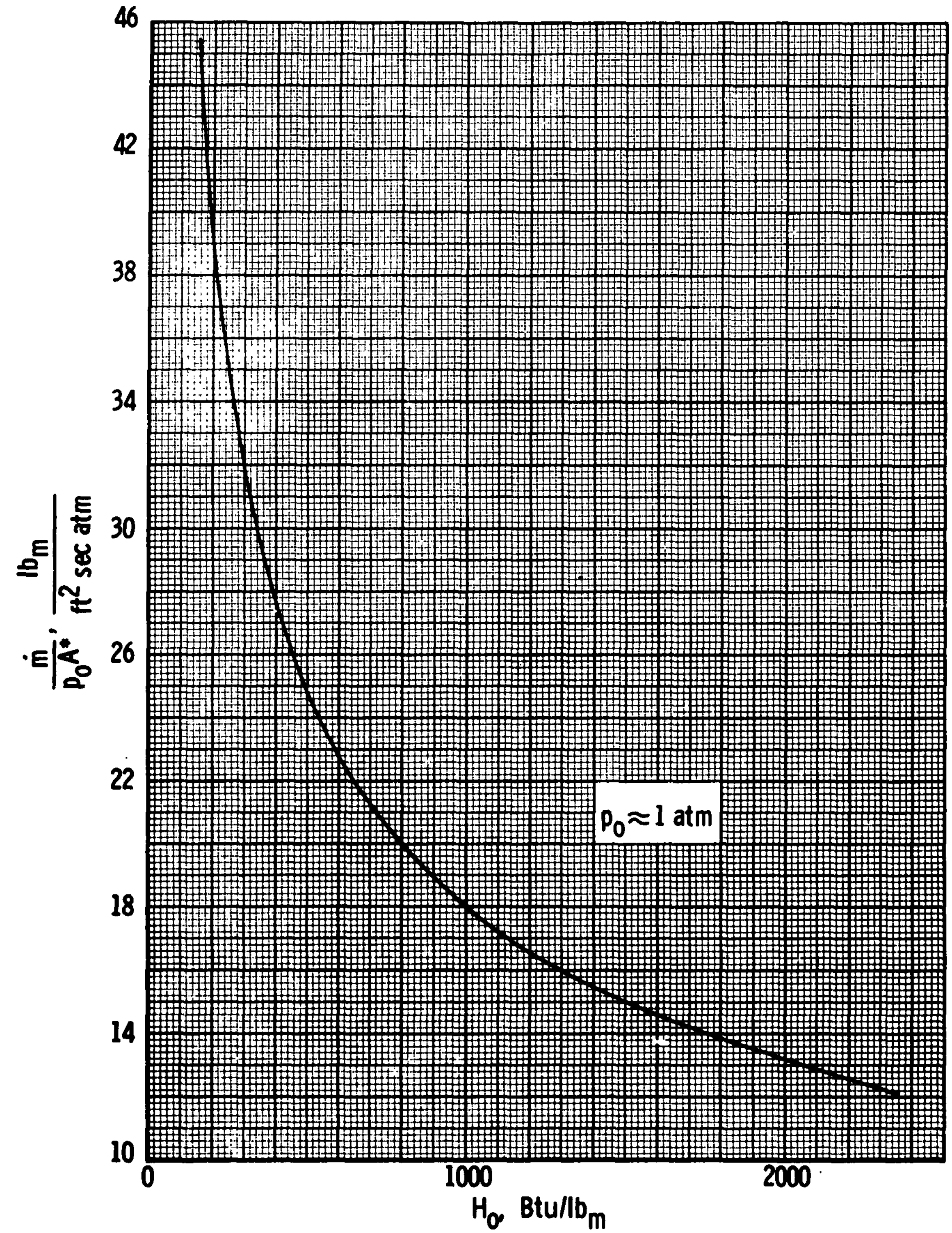

Fig. I-1 Theoretical Calculation for Equilibrium Flow

APPENDIX II

SONIC POINT LOCATION

To obtain an idea as to the location of the sonic point with respect to the nozzle throat, generalized one-dimensional flow with constant specific heat was assumed. The equations for this type of flow can be found from a table of influence coefficients (Ref. 7). The influence of area change, total temperature change, and wall friction on Mach number is given by the following equation:

$$\frac{dM^2}{M^2} = \frac{\left(1 + \frac{\gamma - 1}{2} M^2\right)}{1 - M^2} \left[-2 \frac{dA}{A} + (1 + \gamma M^2) \frac{dT_o}{T_o} + \frac{\gamma M^2 4 f dx}{D}\right] \qquad \text{(II-1)}$$

At the sonic station where M = 1, since the quantity dM^2/M^2 must be finite, Eq. (II-1) requires that

$$-2 \frac{dA}{A} + (1 + \gamma) \frac{dT_o}{T_o} + \frac{\gamma 4 f dx}{D} = 0 \qquad \text{(II-2)}$$

or

$$\frac{dA}{A} = (1 + \gamma) \frac{dT_o}{2 T_o} + \frac{2 \gamma f dx}{D} \qquad \text{(II-3)}$$

From Eq. (II-3) it is seen that in absence of total temperature changes, skin friction would result in a positive dA/A at the sonic point. This can only occur in the diverging section. Similarly, in absence of skin friction, an increase in total temperature will necessitate the sonic point being in the diverging section, and a decrease will necessitate its being in the converging section. Because of the large heat losses near the throat of the LDH tunnel, the total temperature drop may be expected to override the skin friction effect so that, in general, the sonic point will be in the converging section of the nozzle.

To more adequately determine the location, an estimate of the total temperature drop and skin friction was made for a typical set of operating conditions (T_o = 3000 °K, p_o = 17.79 psia, and $\dot{m}$ = 3.6 lb/hr) using the boundary-layer calculation method of Cohen and Reshotko (Ref. 8). Upon substitution of estimated values into Eq. (II-3), there resulted

$$dA/A = -10.26\, dx \qquad \text{with } dx \text{ in ft} \qquad \text{(II-4)}$$

Solution of Eq. (II-4) for the nozzle entrance geometry showed the sonic point to be approximately 0.012 in. upstream of the geometric throat for this particular set of conditions. This implies an A* 0.28 percent greater than the geometric throat area. In view of the accuracy of this calculation, it is assumed that sonic throat area is equal to minimum, geometric, nozzle area.

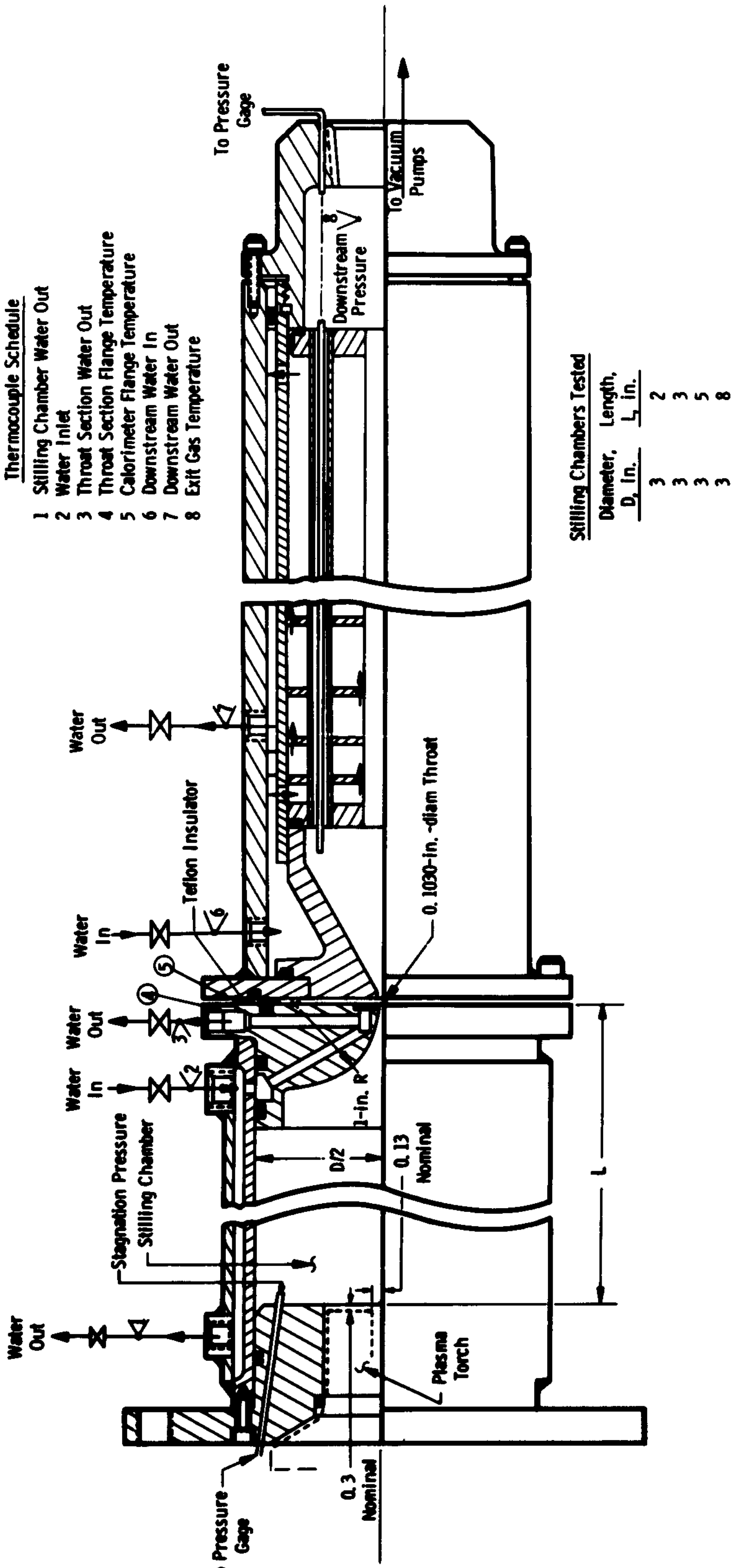

Fig. 1 Total Calorimeter

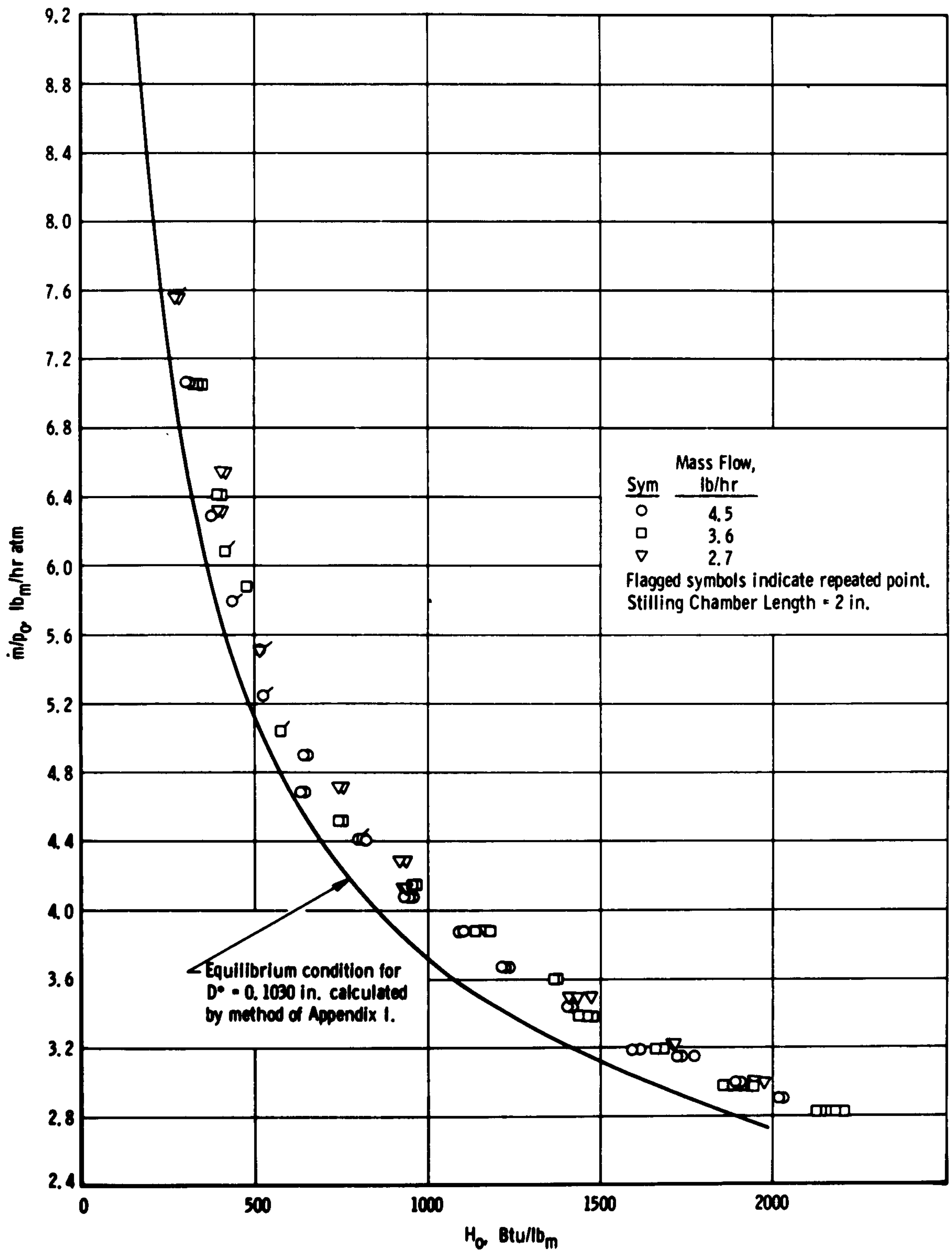

Fig. 2 Total Calorimeter Results for 2-in. Stilling Chamber

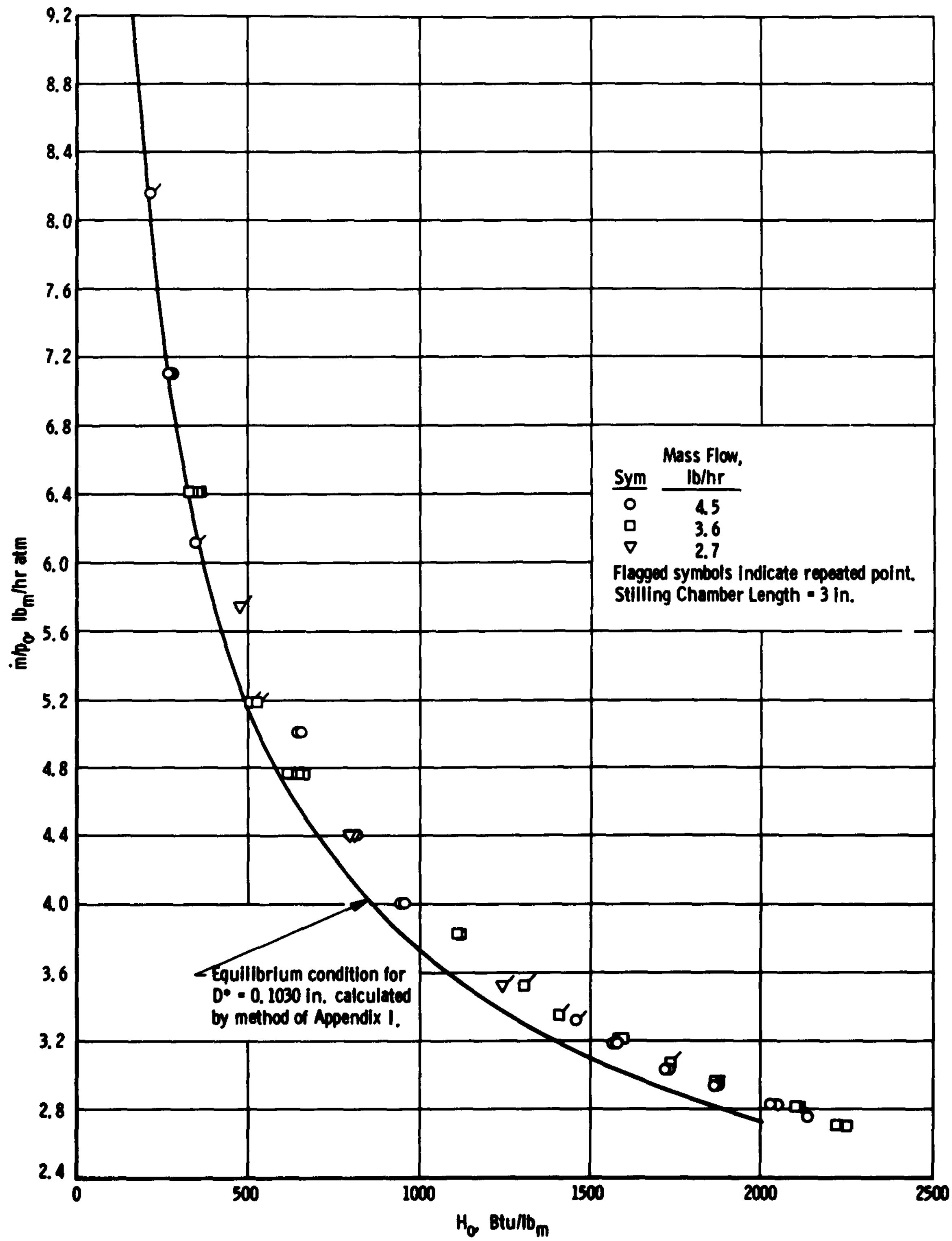

Fig. 3 Total Calorimeter Results for 3-in. Stilling Chamber

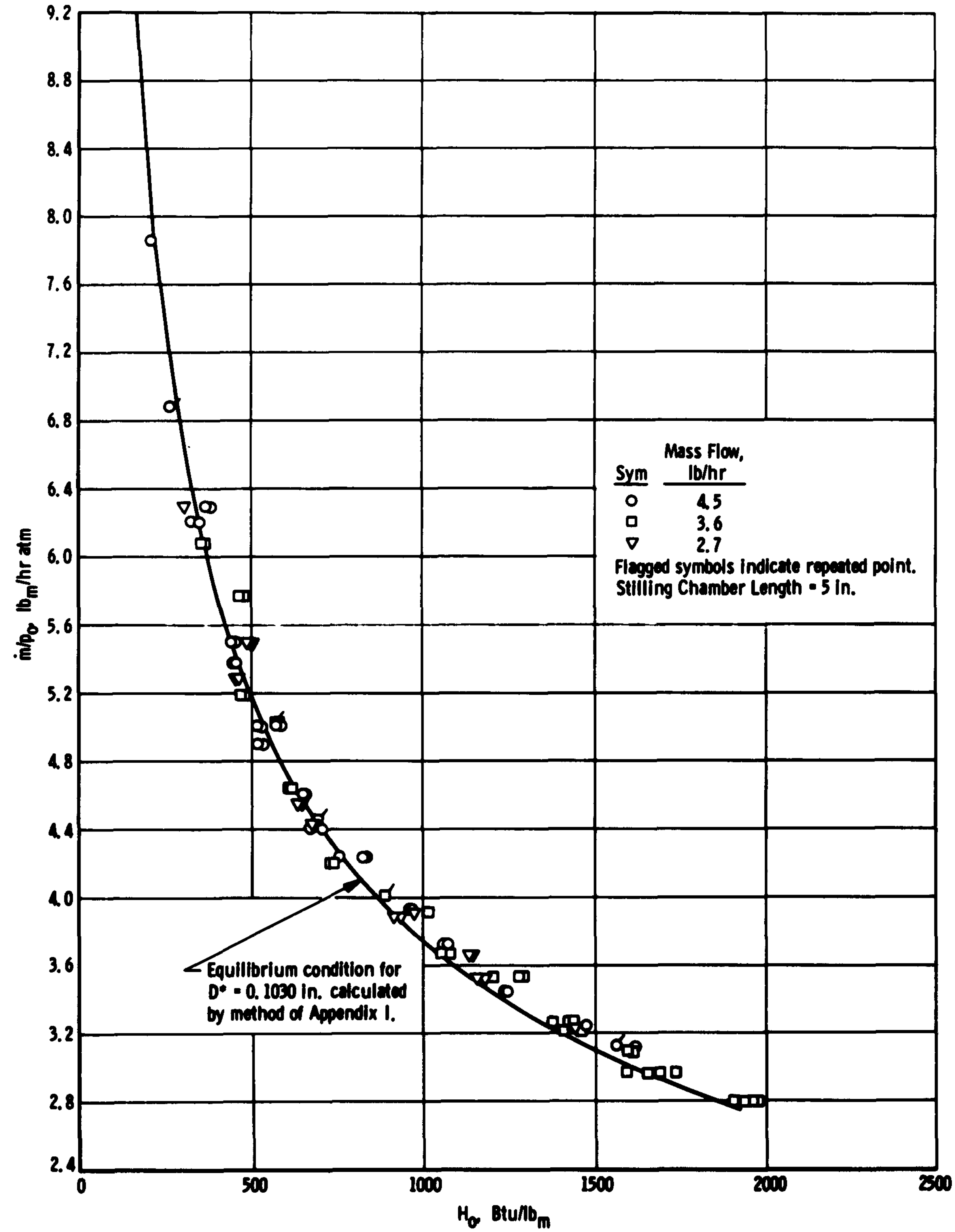

Fig. 4 Total Calorimeter Results for 5-in. Stilling Chamber

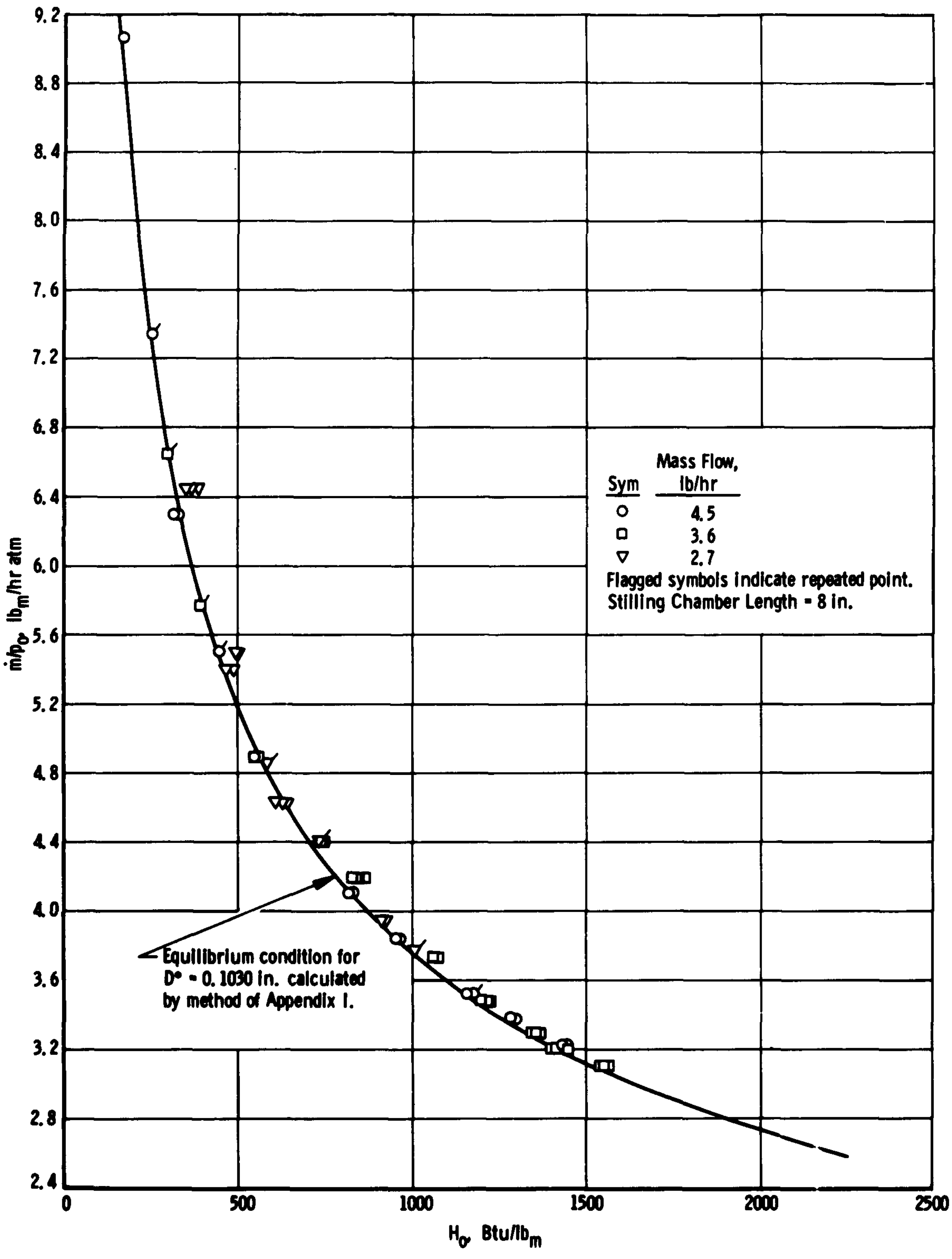

Fig. 5 Total Calorimeter Results for 8-in. Stilling Chamber

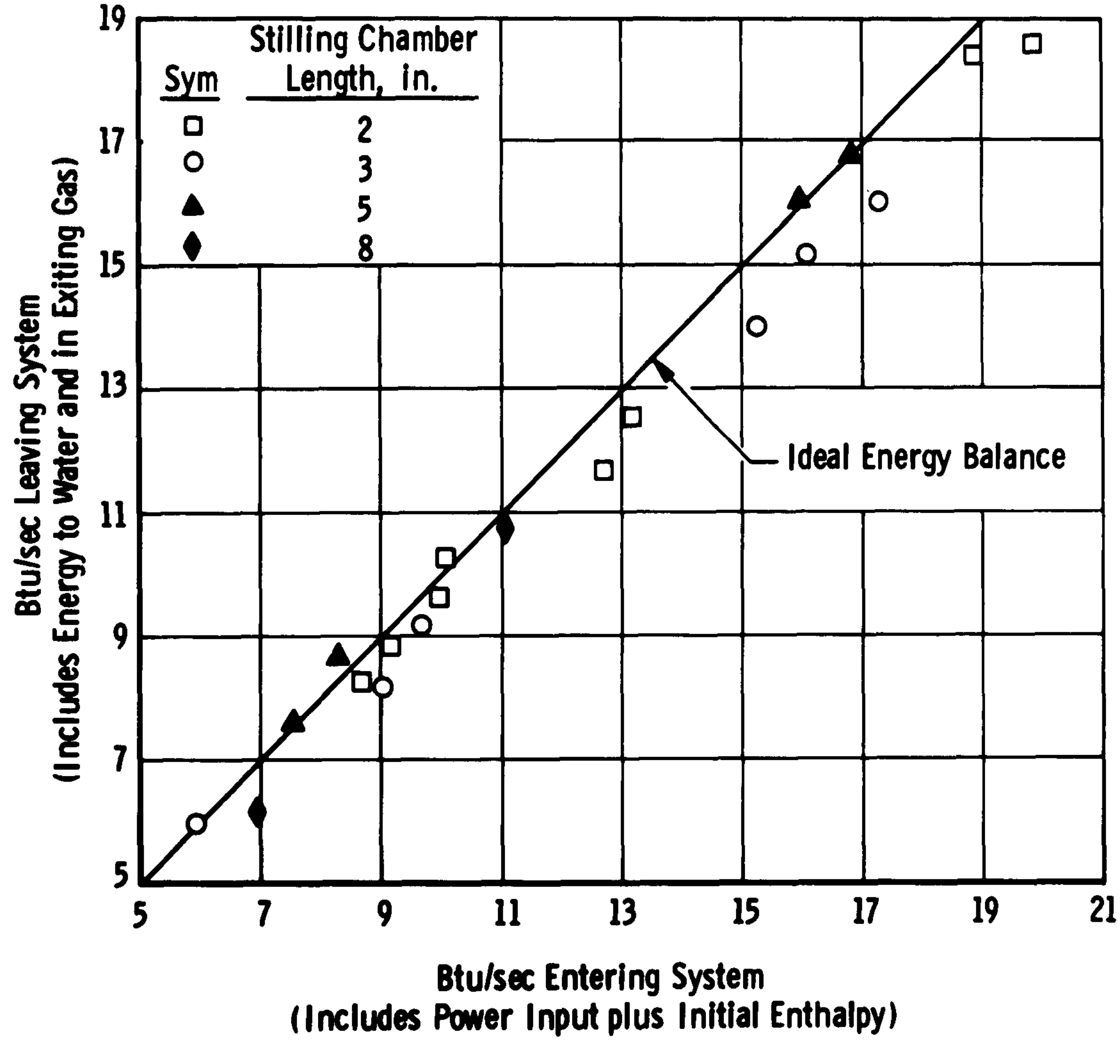

Fig. 6 Energy Balance Results

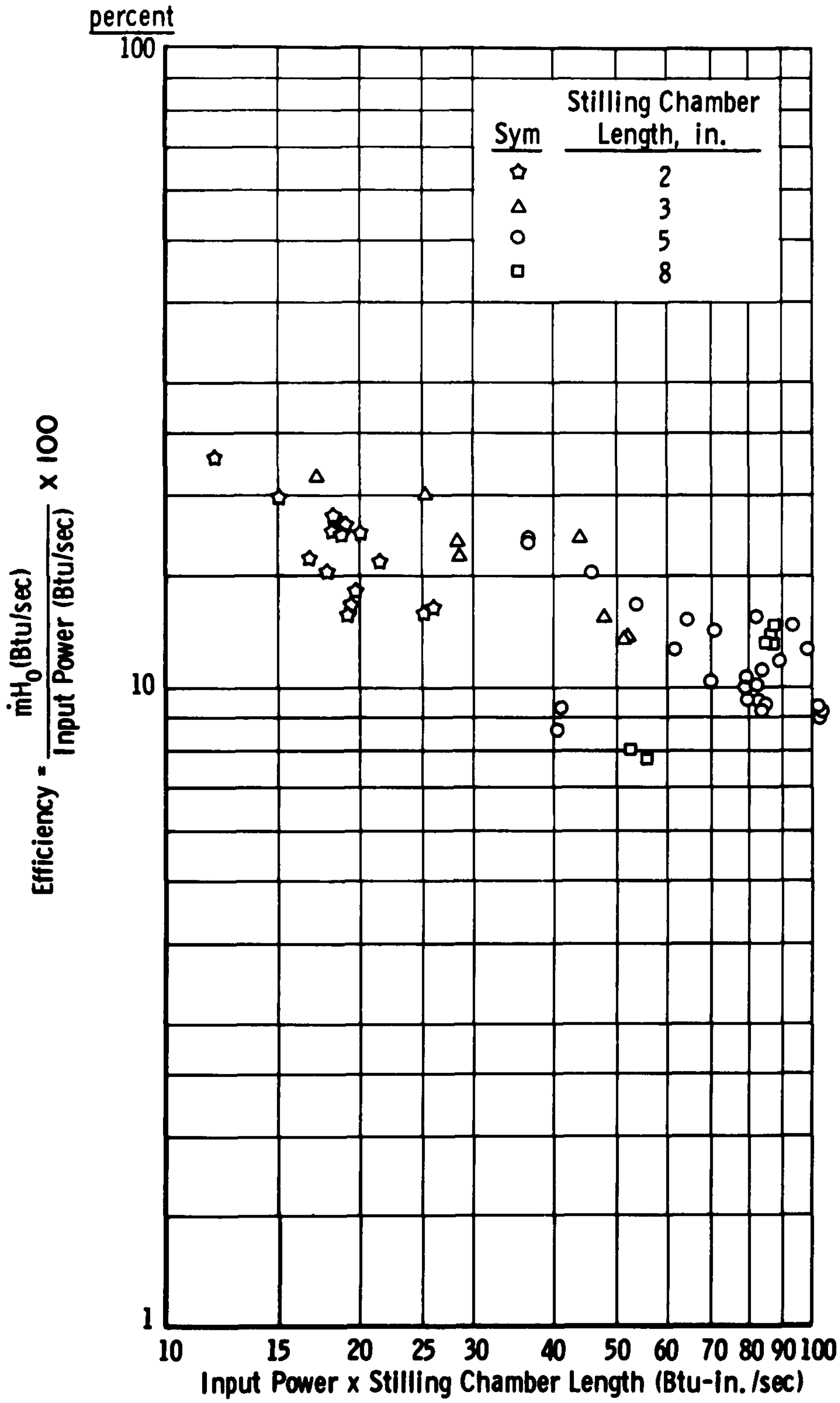

Fig. 7 Combined Heating Efficiency of Arc Heater and Stilling Chamber

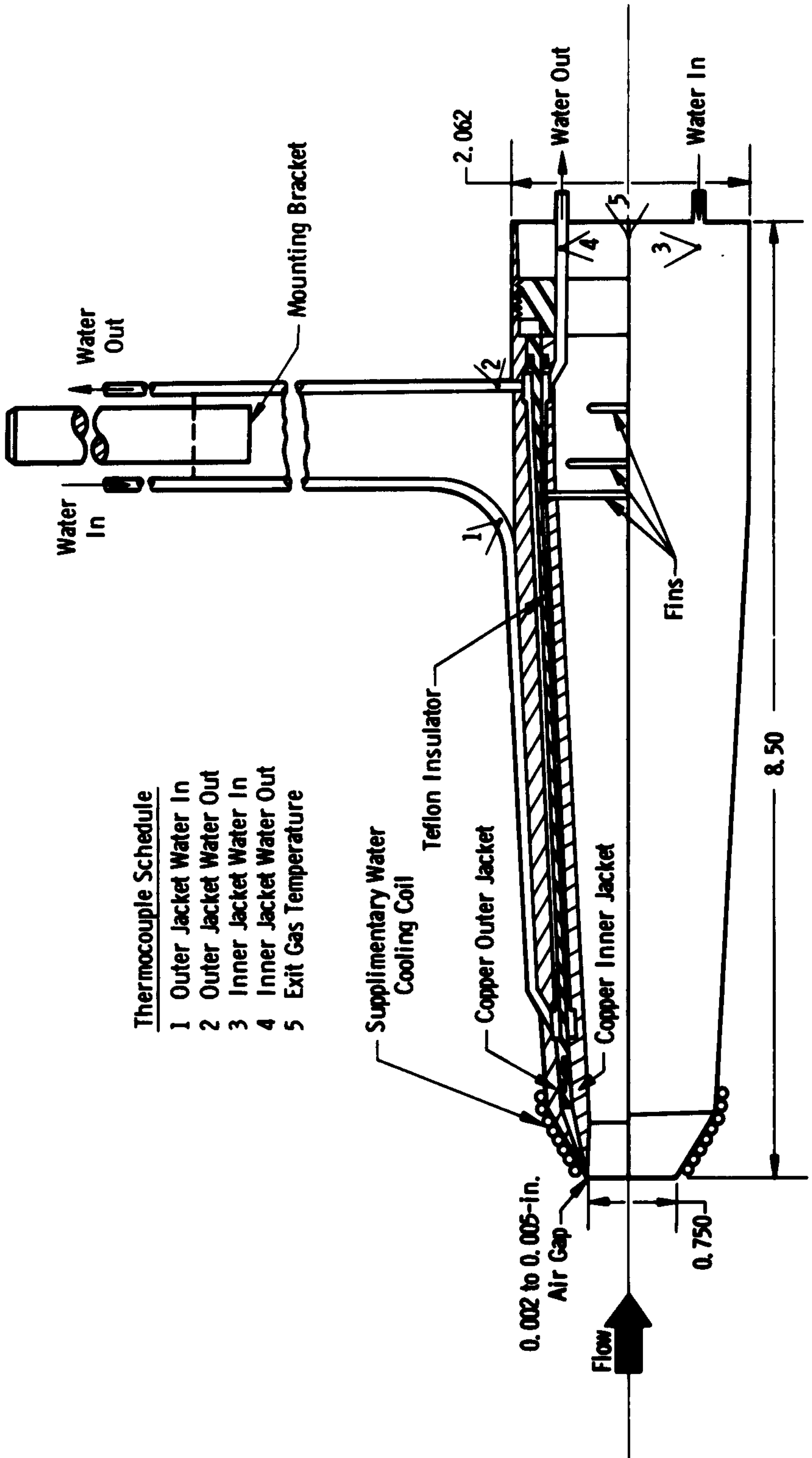

Fig. 8 Calorimeter Probe

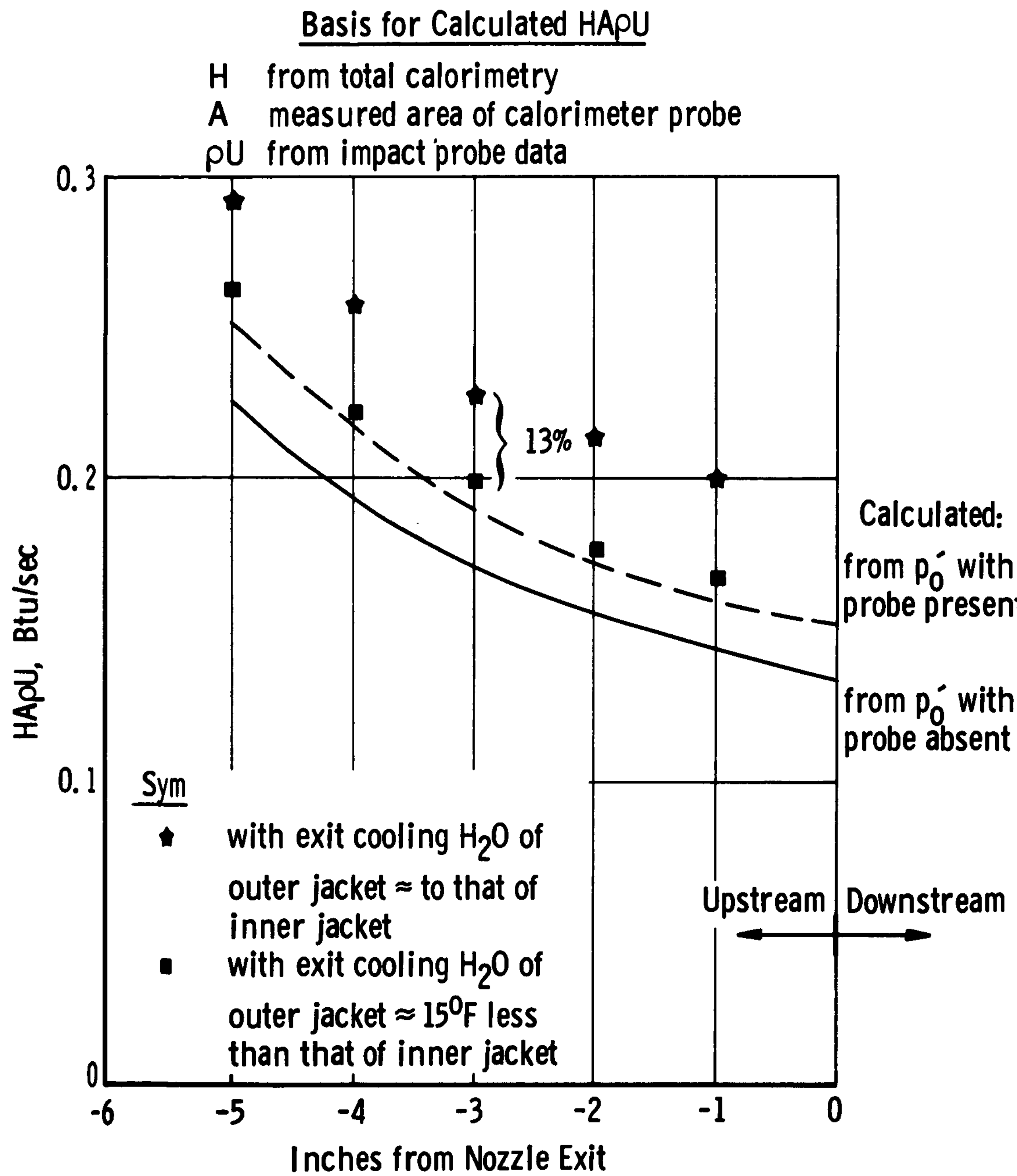

Fig. 9 Calorimeter Probe Results

Arnold Engineering Development Center
Arnold Air Force Station, Tennessee
Rpt. No. AEDC-TDR-63-19. A CALORIMETRIC INVESTIGATION OF SOME PROBLEMS ASSOCIATED WITH A LOW-DENSITY HYPERVELOCITY WIND TUNNEL. February 1963, 37 p. incl 8 refs., illus.

Unclassified Report

Both total calorimeter and calorimeter probe experiments have been carried out to more adequately establish the flow properties in an arc-heated, low-density, hypervelocity wind tunnel. Total calorimeter results show that for a sufficiently long stilling chamber, total enthalpy at the throat can be accurately determined from the total pressure, mass flow rate, and sonic throat area by use of the continuity equation. Unfortunately, the physical size of the calorimeter probe as compared to the size of the test section altered the test-section flow properties so that no useful calibration data were obtained by this means. It is concluded, however, that such a probe could yield useful calibration data in a sufficiently large wind tunnel.

1. Hypervelocity wind tunnels
2. Heat transfer
3. Pressure
4. Calorimeters

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II. Contract AF 40(600)-1000
III. ARO, Inc., Arnold AF Sta, Tenn.
IV. G. D. Arney, Jr., and D. E. Boylan
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